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CORPS OF ENGINEERS, U. S. ARMY

PLASTIC-GLASS FIBER REINFORCEMENT FOR REINFORCED AND PRESTRESSED CONCRETE

REPORT NO. 1

SUMMARY OF INFORMATION AVAILABLE AS OF 1 JULY 1955

TECHNICAL MEMORANDUM NO. 6-421

A
CORPS OF ENGINEERS
RESEARCH AND DEVELOPMENT REPORT

PREPARED BY

WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

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PREFACE

Authority for this study is contained in eighth indorsement dated 21 April 1955 from the Office, Chief of Engineers, to a letter dated 28 July 1954 from the Engineer Research and Development Laboratories, subject, "Request for Project, 'Plastic-Glass Fiber Reinforcement for Reinforced and Prestressed Concrete.'"

This report was prepared under the supervision of Mr. Thomas B. Kennedy, Chief, Concrete Division, by Mr. ~~Bryant Mather~~, Chief, Special Investigations Branch, Concrete Division, Waterways Experiment Station, assisted by Mr. R. V. Tye.

The assistance of the following is greatly appreciated: Mr. Frank M. Mellinger, Director, Ohi River Division Laboratories, who made available a report prepared at his request by Professors N. M. Newmark and C. P. Siess of the University of Illinois; Mr. Ray B. Crepps, Director, Testing Division, Owens-Corning Fiberglas Corporation, Newark, Ohio; Professor Norman J. Sollenberger, School of Engineering, Princeton University, Princeton, New Jersey; and Mr. Perry H. Petersen, Director, Materials Division, Research Department, U. S. Naval Civil Engineering Research and Evaluation Laboratory, Port Hueneme, California.

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SYNOPSIS

Glass has been produced that has a tensile strength of more than 5,000,000 psi. Glass normally has a modulus of elasticity of 5,000,000 to 10,000,000 psi. Cold-drawn steel wire has an ultimate tensile strength of 200,000 to 300,000 psi and a modulus of elasticity of about 30,000,000 psi. Consideration of the use of glass reinforcing in concrete originated in Europe in about 1930 with studies of the possible use of strip glass as a substitute for steel. This work is reviewed but it is probably not directly relevant to current problems. In 1951, Rubinsky began studies of glass fibers as prestressing elements. A considerable amount of work has been done but little has been published. This work is reviewed. The development of glass-fiber reinforced plastics as structural materials for a wide variety of applications has provided much useful background on the combinations and compositions of glass and plastic that may be employed. Glass-fiber reinforced plastic rods have been used as prestressing in experimental concrete beams. The current estimated cost of such rods is about four times that of steel per pound but since they weigh only a third or a quarter as much as steel per unit volume and have about twice the ultimate strength, they may be regarded as potentially more economical. Additional experimental work along lines that can now be described should provide the necessary background to permit the specification of glass-fiber reinforced plastic units as an alternate to steel in prestressed concrete construction.

PLASTIC-GLASS FIBER REINFORCEMENT FOR
REINFORCED AND PRESTRESSED CONCRETE

SUMMARY OF INFORMATION AVAILABLE 1 JULY 1955

PART I: INTRODUCTION

1. Significant developments in the use of glass-fiber reinforced plastics suggested the desirability of a review of research and development work on the use of this material for reinforced and prestressed concrete, and an evaluation of the properties of plastic-glass fiber materials in terms of the requirements for tensioning elements or reinforcement in prestressed concrete members. The results of this review and evaluation are presented in this report.

2. Consideration of the use of glass as reinforcing in concrete appears to have originated in Europe in about 1930. The earliest references to glass reinforcement given in the bibliography compiled by Slate[66*] are to the work of Craemer[20,21,22]. The only other reference prior to 1940 is to Goldstein-Bolocan[36]. These papers have not been examined; consequently, this review begins with material published in 1940. Rubinsky[65] states that he first became interested in glass fibers as tension resistant material in 1916 but did not consider the application to reinforced concrete until 1940.

3. The applications reviewed involve four classes of glass-concrete systems:

a. Solid-glass members as reinforcement.

b. Fiber-glass members as reinforcement.

c. Solid-glass members as prestressing.

d. Fiber-glass members as prestressing.

4. The work of Soden, Lincoln, and Marshall[16,17,18,19,30,31,34] concerns the use of solid-glass members as conventional reinforcement. The Jackson patent is said (Rubinsky[64]) to cover the substitution of fiber

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* Raised numbers refer to the Bibliography at the end of this report.

glass for steel in reinforced concrete. No references to the use of solid-glass members for prestressing have been found. The most promising application appears to be the use of fiber-glass members in prestressing. Rubinsky[63] states that the use of fiber glass instead of steel as simple reinforcement in concrete is not feasible because of the low modulus of elasticity of glass.

5. Stainer[70] has noted that the Corps of Engineers "has been particularly ready to realize the advantages of prestressed concrete construction" and calls attention to the design begun in 1951 of the prestressed spillway bridge at Garrison Dam, the second largest prestressed concrete structure in the United States; and the 216-ft prestressed concrete bridge over the Chesapeake and Ohio Canal at Little Falls, Maryland, which will be the longest concrete girder span in the United States.

6. It is stated in the magazine Engineering[32] for 17 June 1955 that:

> "From the engineering point of view possibly the most significant development in the plastics industry within the last two years is the increasing application of glass-fibre reinforced plastics as structural materials."

PART II: STRIP-GLASS REINFORCEMENT

7. A series of tests on the use of glass strips as reinforcement in concrete was reported in England in the fall of 1940. So far as is known, the first report was in Civil Engineering for August 1940[17], and stated that the successful use of glass in place of steel as reinforcement for concrete had been announced. The research had been initiated at the outbreak of war but the results indicate that glass reinforcement may be of use on its own merit and not merely as a wartime substitute. The tests were conducted by A. W. Soden and J. A. Lincoln, and the results were submitted to E. H. Paisley of the Borough of Kensington for consideration in connection with the construction of concrete air-raid shelters. Independent tests were subsequently made at the City and Guilds College Structural Laboratory. The technical data given by this account include the following:

"The results of these tests have shown that slabs of glass-reinforced concrete would carry four times the maximum load required by the Home Office for street and other air-raid shelters.

"In reinforced concrete beams steel rods are embodied in the lower edge to take the whole of the tension which is equal to the compression taken by approximately the top third of the concrete. The remaining two-thirds of the concrete is mechanically wasted as regards load-bearing and merely acts as a binding agent and shear. It has been found, according to the report of the investigators, that by substituting glass reinforcement for steel the neutral axis is lowered and more concrete is brought into play for compression. And as the glass cross-sectional area is three times as much as steel, little concrete is wasted.

"The glass reinforcement so far used is in strips 5/16 in. thick, the depth being half the depth of the beam which it is to reinforce. An important feature is that one edge of the glass is not cut but is the fire-finished edge, known as the selvedge, in the state in which it comes from the process.

"For reinforcement requirements, it is stated, polishing and refining weaken the glass, and the cut edge is incapable of taking strain.

By placing the glass strips in the beam or slab so that the cut edge is at the neutral axis and the selvedge lowermost, the stress taken by the glass, although only half that of rod form is practically and scientifically balanced. In this form also, wear does not need to be provided for.

"In the early stages there are, of course, certain disadvantages, notably the present limit in span and a lower impact load. The present application is mainly concerned with the problem of surface air-raid shelters and here the difficulty is easily overcome by a number of methods. Finally, there is the absence of yield before failure. These disadvantages revealed by initial tests will be subjected to further research.

1. Position of Neutral Line

In calculating proportions to be adopted in cross section the limiting stresses which can be allowed in the top and bottom of the section are used to give the proper position for the neutral line.

The data assumed for concrete and glass are as follows:

Young's Modulus: -

Concrete - 2,000,000 lb./sq. in.

Glass - 10,000,000 lb./sq. in.

Limiting Safe Stresses: -

Concrete - 600 lb./sq. in. (in compression)

Glass - 2,500 lb./sq. in. (in tension, fire-finished surface)

In a beam of depth d in., the neutral line will be at a depth from the top such that when the compression in the top layer introduces a compressive stress 600 in that layer, the tensile stress in the bottom layer will be 2,500. Since glass has a Young's Modulus five times that of concrete, the relative compression and extension to give these stresses will be proportional to 600 and 2,500/5, i.e., 600 and 500. This compression and the corresponding extension are proportional to the distances of the upper and lower surfaces of the beam from the neutral line, consequently if the full depth of the beam is represented by 11, the compression zone (from the top down to the neutral line) will be represented by 6, and the tension zone (from the neutral line to the bottom of the beam, is of depth 5.

2. [illegible]

Since glass is so much weaker than steel a relatively large cross-sectional area will be needed, and it cannot be assumed that the glass can be introduced as a thin rod with its centre at the lower limit of the tension zone. No part of the glass must lie below this limit, otherwise it would be stressed to an amount greater than 2,500 lb./sq. in. when the concrete is loaded to 600 lb./sq. in.

It is, therefore, necessary to imagine the glass to be distributed throughout the full depth of the tension zone in order to find what cross-sectional area may be needed. This gives in effect a composite beam. The breadth at the top can be denoted by b, and the breadth at the bottom by y.

When the beam is loaded, the position of the neutral axis is such that the compressions in the concrete must just balance the tensions in the glass, i.e. $1/2\ 600 \times 6b = 1/2\ 2{,}500 \times 5y$, which gives $36b = 125y$, or

$$y = \frac{36b}{125} = .288b$$

The stresses will be balanced, therefore, if the width of the glass section is only 0.288 times the width of the concrete. For convenience it will be taken that $y = 0.3b$.

3. Suggested Construction.

The foregoing results indicate that the most economical construction would be to construct the beam of uniform cross section throughout, the upper half being solid concrete and the lower half being made with vertical strips of glass embedded in the concrete at distances such that the separation between the strips is 2-1/3 the thickness of each strip. The vertical dimensions of the strips would be not quite equal to the half-depth of the beam, this would be made up allowing a small 'cover' for the under edges of the glasses.

It would be of some advantage to allow the glass to penetrate a little way above the neutral line so as to ensure the top (cut) edge being in compression.

4. Strength of Glass-Reinforced Girder.

If the stresses across 1 in. of the section are considered to obtain the limiting bending moment, it must be assumed that the depth of the girder has some value <u>d</u> inches, including the 'cover' of concrete on the underside below the glass.

Then equivalent force (compression) in concrete = 1/2 600 x .5<u>d</u> = 150<u>d</u> . The effective line of action of this force is at a depth 1/6<u>d</u> below the top surface, i.e. at a distance 1/2<u>d</u> above the neutral level.

Equivalent force (tension) in glass = 1/2 2,500 x

$$\frac{5d}{12} \times \frac{3}{10} .$$

(The 3/10 factor comes in because the glass occupies only 3/10 the full width of the girder, the rest being concrete of no tensile strength.) So equivalent force in glass 156.5<u>d</u>.

The discrepancy between this value and 150<u>d</u> is due to taking the strip as occupying 3/10 the width instead of 36/125; both values will be taken as 150<u>d</u>.

Table I

Details of Reinforcement of Specimens

Specimen No.	Cross Section	Length	Reinforcement
1	12 in. x 4-1/2 in.	4 ft. 6 in.	10 strips at 1-1/2-in. centres
2	12 in. x 4-1/2 in.	4 ft. 6 in.	10 strips at 1-1/8-in. centres
3	12 in. x 4-1/2 in.	4 ft. 6 in.	6 strips at 2-in. centres
4	12 in. x 4-1/2 in.	4 ft. 6 in.	6 strips at 2-in. centres
5	12 in. x 4-1/2 in.	4 ft. 6 in.	10 strips at 1-1/8-in. centres
6	12 in. x 4-1/2 in.	2 ft. 3 in.	10 strips at 1-1/8-in. centres
7	12 in. x 4-1/2 in.	2 ft. 3 in.	6 strips at 2-in. centres

Table II

Results on Bending Tests

Specimen No.	Bending Moment First Crack lb./in.*	Bending Moment Failure lb./in.	Design Moment (Soden) lb./in.	Factor of Safety
1	56,300	64,800	26,700	2.43
2	60,500	61,800	26,700	2.31
3	34,500	45,300	16,000	2.83
4	43,800	45,100	16,000	2.82
5	57,000	63,600	26,700	2.38

* Dimensions of bending moment should be stated as: lb.-in. Ed.

Effectively the force in the glass acts at a distance of $\frac{2}{3} \times \frac{5d}{12}$ below the neutral line.

The total bending moment is thus equal to:

$$150\underline{d} \times \left(\frac{1}{3} + \frac{10}{36}\right)\underline{d} \text{ lb./in.}$$

or

$$150 \times \frac{22}{36}\,\underline{d}^2 \text{ lb./in.}$$

If $\underline{d}$ is 6 in. this gives:-

Total B.M. per in. width = $150 \times \frac{22}{36} \times 36$ lb./in. = 3,300 lb./in.

For a beam 1 ft. wide limiting B.M. 39,600 lb./in.

A girder for A.R.P. shelters must be capable of withstanding a uniform static load of 450 lb. per sq. ft. (in addition to its own weight).

The maximum bending moment due to a distributed load of 450 lb. per sq. ft. would be given by $\frac{\underline{m}l^2}{8}$ where $\underline{m}$ is the load per sq. ft. and l the length of the span.

For a 4 ft. 6 in. span this gives:-

Maximum bending moment

$$= \frac{450 \times 4.5^2}{8} \text{ lb./ft.}$$

$$= \frac{9,112}{8} \text{ lb./ft.} = \frac{12}{8} \times 9,112 \text{ lb./in.}$$

$$= 13,668 \text{ lb./in.}$$

The weight of the girder itself would be about 90 lb. per ft. run if the depth were 6 in., consequently the total bending moment would be about 13,668 + 2,734 lb./in., or say 16,500 lb./in.

According to these calculations, therefore, a girder constructed as suggested in Section 3 would be more than twice as strong as is necessary according to the A.R.P. Specification (revised code) for shelter roofs.

If the depth of the girder were reduced to 5 in., keeping the proportions the same, the limiting bending moment would be reduced to 27,500 lb./in. Reduction to 4 in. (too thin for A.R.P. Specification) would still give a limiting bending moment of 17,600 lb./in. which would be more than sufficient to withstand the load specified.

Allowing for the reduced weight of the girder itself, the bending moment would be about 15,500 lb./in. in this case.

A 6-in. steel-reinforced concrete girder with centre of reinforcement 5 in. from the underside would give values as follows:-

Force in concrete $\frac{1}{2}$ 600 x .36$\underline{d}$ = 108$\underline{d}$.

Mean line of action is .12$\underline{d}$ below top of girder.

Force in steel is also 108$\underline{d}$, or should be, and it acts at a distance $\underline{d}$ from the top.

Maximum bending moment is thus 108$\underline{d}$ x .88$\underline{d}$ = 108 x 88$\underline{d}^2$.

For a 6-in. girder, the effective value of $\underline{d}$ is 5 in., so:-

Maximum bending moment for 6-in. girder

= 108 x .88 x 25

= 950.4 x 25

= 2,375 lb. in. per in. width.

= 28,400 lb. in. per ft. width.

"This steel reinforced girder would be approximately 72 per cent stronger than is necessary to carry the 450 lb. load per sq. ft. The 6-in. glass-reinforced girder, on the other hand, would be 140 per cent stronger than necessary.

"The concrete used throughout the tests which were carried out at the City and Guilds College Laboratories under the direction of W. J. Marshall, was a 1:2:3 mix of rapid hardening Portland cement, well-graded clean river sand and 3/ -in. ballast, except for specimen 5, where a 1/4-in. ballast was used for the concrete between the glass strips. A wetter mix was used for the lower part of the beams to facilitate consolidation.

"The glass reinforcement was supplied by Pilkington Brothers, Ltd., and consisted of strips averaging 5/16 in. thick by 2-1/4 in. deep. Details of the specimens are given in Table I.

"In each case the glass was placed vertically with the bevelled edge flush with the underside of the slab. Test cubes were also made to give the crushing strength of the concrete used. The specimens were in all cases tested after seven days.

"The tests carried out were of two types (a) bending, and (b) impact.

"The bending test was carried out on specimens 1 to 5 in a Riehle test machine. The beams were supported at 4-ft. center, plywood strips being placed over the knife edges to eliminate local crushing on the glass. Point loads were applied at a distance of 15 in. from each support.

"The results of the tests are summarized in Table II.

"Deflection readings taken during the test showed no appreciable deflection at one-third of the failing load and at about 60 per cent of the failing load the deflection was 0.02 in. Failure came suddenly and was of the type usually obtained with brittle materials: on reaching the maximum load complete collapse occurred as distinct from ordinary reinforced concrete, where complete collapse does not occur until some time after the maximum load has been reached.

"The impact tests were carried out by dropping a 16-lb. weight from various heights on to the specimen which was supported at 1 ft. 9 in.

centres on a plaster of Paris bed 1 in. wide. The results of the tests were as follows:-

Specimen No. 6.- Ball dropped from 6 ft. height caused slight cracking on some of the glass strips; on again dropping the ball from the height very appreciable cracking of the glass occurred, the upper surface of the concrete was not damaged.

Probably ultimate momentum absorbed 112 ft./lb.*

Specimen No. 7.- Ball dropped from 4 ft. height had no effect; ball dropped from 6 ft. height caused complete failure.

"Probably ultimate momentum absorbed 68 ft./lb.*

"It is realized that these tests as they stand have little value, due to lack of figures for an ordinary reinforced concrete slab under similar conditions, but a summary of certain impact tests on reinforced concrete may provide useful comparison.

"A concrete slab 2-1/2 in. thick reinforced with .094 sq. in. of steel and supported at 2 ft. 6 in. centres absorbed 144 ft. lb.* of momentum and showed failure by crushing of the concrete at the point of impact and spalling-off on the underside.

"The crushing tests on the concrete cubes gave an ultimate strength in direct compression of 3,920 lb./sq. in.

"The report on the tests concludes that the factor of safety for specimens 3 and 4 is comparable with ordinary reinforced concrete under similar tests, that for specimens 1, 2 and 5 is somewhat lower. The safe moment was based on the values given by Soden. The impact tests compare unfavorably with ordinary reinforced concrete. Marshall's recommendations are that for static loading of such an intensity that the reinforcement need not be placed closer than 2 in. centres, glass provides a good substitute for steel. In cases, however, where there is any likelihood of impact loading it should not be used."

8. Additional results were presented by a subsequent account in October 1940[18]:

"Further research has been carried out with a view to increasing

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* Should be ft.-lb./sec. Ed.

the s[illegible] possible, and it is now claimed that all ordinary loading can safely and economically be carried on spans at present limited by economy, up to 20 ft. Columns can also be reinforced successfully it is stated.

"The economic employment of glass giving double the present strength depends solely on a large-scale demand, it is stated. There is no difficulty in handling, it does not require skilled labor and intricate calculations. There is no bending, wiring, or stirrups. The small deflection of glass reinforced concrete is an advantage and the drawback of weakness to impact loads can be offset in the interim of further research, by use of higher factor of safety figure.

USE OF 'LAPPING'

"The discovery of 'lapping' enables given length of glass reinforcement to span nearly twice its own length.

"Immediate uses possible are government huts, hospitals, storage tanks, fuel containers, railway sleepers, earth-covered air-raid shelters and general wartime and emergency building.

"It should be clearly borne in mind that the results so far are not conclusive but are the immediate discoveries of preliminary investigation in what is proving to be a new and wide field for discovery and research.

"Further tests were carried out by Mr. W. T. Marshall and his report is reproduced below:

"[illegible].- The concrete used throughout the tests was a 1:2:3 mix of rapid hardening portland cement, well-graded clean river sand and Thames ballast. For the concrete between the glass strips a 1/2-in. aggregate was used and for the portion of the beam above the glass 3/4-in. aggregate was used. A wetter mix was used for the lower part of the beam to facilitate consolidation.

"The glass reinforcement consisted of strips 1/4-in. thick. In each specimen the glass strips were placed vertically, the fire-finished edge being given 1/2-in. cover of concrete on its underside. Templates were used to keep the glass in position.

"Details of the specimens are given in Table I.

Tests- The objects of the tests were as follows:

1. To determine the resistance moment of 12 in. x 7 in. and 9-1/2 in. x 4-1/2 in. sections.

2. To determine the grip length or 'lap' required for glass reinforcement.

3. To design a beam of long span using short lengths of glass with the lap previously determined and to test such a beam.

The specimens were in all cases tested in bending, the tests being carried out in a Riehle test machine.

For specimens 1 to 10 the test was carried out on a 6-ft span, and for specimens 11 and 12 on a 9-ft span, the loads being applied at the third points in each case. Specimen 13 was tested on a 16-ft span, the loads being applied at 5 ft. 6 in. from each support.

During the test the deflection at the centre of the span was measured by a Mercer dial and from these readings the modulus of elasticity of the material was calculated.

Dealing firstly with specimens without lap where the object of the tests was as given under heading (1) above, the results can be summarized as in Table II.

The failure occurred in all cases by tension and was of the type associated with brittle materials. In most cases a preliminary crack occurred at about 90 per cent of the failing load.

The deflection readings taken gave an average value for the modulus of elasticity of 3.5×10^6 lb. per sq. in. which is approximately the same as that for plain concrete.

To carry out a complete series of tests to determine the bond between glass and concrete and the distribution of bond stress over the depth of the section was beyond the scope of the present series and the following simple method was used to determine the grip length required for a glass strip 5-7/8 in. deep. The beams 6 to 10 were made with short strips of glass of the lengths stated in Table I, thus giving laps varying from 1 ft. 6 in. to 2 ft. Specimens 4 and 5 gave the strength of a beam using continuous reinforcement and by comparing the strength of the

beams with lapped reinforcement with these beams it was possible to determine the amount of lap required to give the same strength.

It is realized that this is a very inadequate method of tackling the problem, but it is suggested that it provides some useful information as a prelude to further work.

The results of the tests summarized in Table III showed that 2 ft. was sufficient lap for the glass used in these beams.

The failure was similar to the other beams tested, i.e. a tension failure, the fracture section occurring in each case at the end of the lap.

The deflection readings gave the same value for the modulus of elasticity as for the unlapped reinforcement.

The final problem in this series of tests was to use lapped reinforcement in designing a beam of long span using only glass strips less than 10 ft. long.

By stopping off the reinforcement to match the bending moment diagram and using a lap of 2 ft. it was found possible to keep the maximum length of reinforcement 9 ft. 6 in. in a beam of span 16 ft.

The beam failed at a load of 8,130 lb. by a tension crack 18 in. from the centre of span. This corresponds to a bending moment of 269,000 in./lb., the moment taken by a similarly reinforced section (Specimens 1 and 3) without laps was 283,000 in./lb., thus giving a ratio of 0.95 between the two strengths.

This test was very satisfactory as it showed that the value of 2 ft. taken for the lap in the design of the beam was satisfactory.

Conclusions.- It has already been stated in the previous tests carried out for the Kensington Borough Council that glass should not be used as reinforcement when impact loads are likely but these tests confirm the fact previously stated that for static loading glass makes a suitable reinforcement for concrete. The feature of the test has been the consistency of the behavior of the material, only one reject result having been obtained in the whole series.

Table I

Specimen	Cross Section of Concrete	Length	Reinforcement
1	12 in. x 7 in.	6 ft. 4 in.	7 strips, 5-7/8 in. deep, 6 ft. long
2	12 in. x 7 in.	6 ft. 4 in.	7 strips, 5-7/8 in. deep, 6 ft. long
3	12 in. x 7 in.	6 ft. 4 in.	7 strips, 5-7/8 in. deep, 6 ft. long
4	12 in. x 7 in.	6 ft. 4 in.	4 strips, 5-7/8 in. deep, 6 ft. long
5	12 in. x 7 in.	6 ft. 4 in.	4 strips, 5-7/8 in. deep, 6 ft. long
6	12 in. x 7 in.	6 ft. 4 in.	8 strips, 5-7/8 in. deep, 4 ft. long, with central lap of 2 ft.
7	12 in. x 7 in.	6 ft. 4 in.	
8	12 in. x 7 in.	6 ft. 4 in.	8 strips, 5-7/8 in. deep, 3 ft. 10-1/2 in. long, with central lap of 1 ft. 9 in.
9	12 in. x 7 in.	6 ft. 4 in.	
10	12 in. x 7 in.	6 ft. 4 in.	8 strips, 5-7/8 in. deep, 3 ft. 9 in. long, with central lap of 1 ft. 6 in.
11	9-1/2 in. x 4-1/2 in.	9 ft. 4 in.	4 strips, 4-1/2 in. deep, 9 ft. long
12	9-1/2 in. x 4-1/2 in.	9 ft. 4 in.	
13	12 in. x 8 in.	16 ft. 6 in.	See sketch

Table II

Specimen No.	Failing Load	B. M. at Failure	Design Moment (Soden)	Factor of Safety
1	25,290 lb.			
2	19,060 lb.*			
	23,900 lb.			
Av.	24,600 lb.	288,000 in./lb.†	91,500 in./lb.†	3.15
4	15,360 lb.			
5	17,980 lb.			
Av.	16,660 lb.	199,000 in./lb.	52,300 in./lb.	3.81
11	5,560 lb.			
12	5,330 lb.			
Av.	5,450 lb.	98,200 in./lb.	33,000 in./lb.	2.98

* Reject result.
† Dimension of bending moment should be stated as: lb.-in. Ed.

Table III

Specimen No.	Lap	Failing Load	B. M. at Failure	Ratio $\frac{\text{Strength}}{\text{Strength of Unlapped}}$
6		16,870 lb.		
7		15,810 lb.		
Av.	2 ft.	16,340 lb.	196,000 in./lb.	0.985
8		13,970 lb.		
9		15,470 lb.		
Av.	1 ft. 9 in.	14,720 lb.	176,500 in./lb.	0.886
10	1 ft. 6 in.	11,070 lb.	132,800 in./lb.	0.666

"FACTOR OF SAFETY

"Apart from inability to resist impact the main criticism to make against the reinforcement is the value of the safe resistance moment calculated by Soden. The factor of safety based on this moment varied in the Kensington tests from 2.3 to 2.8, in the present series it varied from 2.95 to 3.81. The increase in the present tests was probably due to the 1/8-in. cover of concrete on the underside of the glass: as this will be used in practice the values obtained in the present series may be taken as representing the true case.

"The generally accepted value for the factor of safety for ductile materials is 3.5: for brittle materials it is much higher, generally of the order of 10. Glass reinforced concrete is definitely brittle material and to use the low factor of safety which Mr. Soden's figures give is definitely bad practice.

"The tests show that the ultimate resistance moment of a glass reinforced beam can be expressed empirically by the formula:

$$M = 1{,}250\, td^2$$

where t = total thickness of glass plates used,

d = depth of beam measured to edge of glass reinforcement.

"It may thus [illegible] of the ultimate resistance moment of the section it deals with [illegible] the material to adopt, what, in their opinion, is a satisfactory value for the factor of safety for the conditions under which the material is being used.

"This report must not be taken as conclusive evidence on the value of glass as reinforcement. Much more exhaustive tests would have to be carried out before it could be universally adopted. In these tests certain problems which were of interest to the parties concerned have only been investigated, and the report should not be taken as a thorough investigation of the subject."

9. A similar pair of articles appeared in Engineering[30,31] in 1940 and the information was also summarized in other journals. Emphasis

was placed on the reports particularly because of the possibility they seemed to offer of reducing materially the heavy demand for steel. It was reported that the bonding of the concrete to the glass was excellent.

PART III: FIBER-GLASS REINFORCEMENT

Work of Rubinsky

15. Prior to 1951 references to glass reinforcement primarily concerned solid glass rods and strips. The first consideration of glass fibers appears to have been by Professor Ivan A. Rubinsky. Evidently the first account of his work that was published in the United States was in the Engineering News-Record[33] for 1 March 1951, and stated in part:

"Engineers all over the world are now well aware of the many benefits of prestressed concrete. But in many countries, they cannot take advantage of this material because of the lack of high-strength steel for prestressing. In these - as well as in other parts of the world - engineers may fine substitution of glass cords or strands for steel well worth while.

"This is the suggestion of Ivan A. Rubinsky, associate professor of engineering and physics at the American University, Beirut, Lebanon. He is at present in the United States on a visit.

"Professor Rubinsky points out that the raw materials for making glass - pure silica sand or borosilicates - can be found practically anywhere and in unlimited quantities. Manufacturing processes are available for forming glass fibers, which can be made into cords or strands. And only a small quantity of this material is required relative to steel - for a prestress beam, perhaps one to two per cent of the weight of ordinary reinforcing steel in an equivalent reinforced concrete beam.

"Glass fibers have practically no plasticity. They retain their elastic properties until they break. Thus, residual strains are nearly nonexistent.

"Other advantages of this material, according to Professor Rubinsky, are high resistance to acids and alkalies and ability to withstand high temperatures. Thus, concrete prestressed with glass fibers would be more fireproof than ordinary reinforced concrete and immune to the corrosive action of sea water and many chemicals.

"Furthermore, the professor says, the low modulus of

elasticity of glass cords (about 6,000,000 psi) is an advantage. With prestressed concrete, the lower the modulus of elasticity of the prestressing element, the smaller will be loss of prestress due to shrinkage, temperature change and plastic flow of concrete.

"It is a well established fact that glass fibers have great tensile strength. Professor Rubinsky notes that strengths as high as 5,200,000 psi have been reported for silica fibers 0.00012 in. in diameter. He expects, however, due to uneven distribution of stress, the strength of cords made of such fibers will be considerably less than the sum of the strengths of individual fibers. Nevertheless, ultimate strength values above 1,000,000 psi can be anticipated. Hence, the amount of glass fiber required for prestressing is about one-fourth the volume of 225,000-psi cold-drawn steel wire, and one-fourteenth the weight.

"The problem of introducing glass into prestressed concrete construction, however, is not simple. One complication is that the tensile strength of glass fibers decreased with increasing diameter. Also, the effect of irregularities and cracks must be taken into account.

"These defects may explain the variation in strength with diameter. The smaller the fiber, the smaller the number of irregularities, and hence, the greater the possibility of a higher average ultimate stress. It is also possible to suppose that when a fiber is formed, defects are elongated parallel to the axis of the fiber. The finer the fiber, then the more elongated the defects. This elongation of defects, especially of those on the surface, may reduce local stresses and so increase ultimate strength.

"Another physical property affecting the use of glass fiber in prestressed concrete is the difference in strength between dry fibers and wet ones. Experiments have shown that strength may increase 2.5 to 4 times in a vacuum, that is, when absorbed moisture is completely eliminated. One explanation for failures at relatively low values in humid atmospheres is that surface cracks and defects in the fibers are filled with silica gels. These swell when exposed to humidity, setting up internal stresses and decreasing the strength of the fibers.

"Another problem that designers of glass-fiber prestressed

concrete would encounter is that of obtaining equal distribution of stress among fibers of a strand or cord. Experiments have shown that the strength of a glass strand may be over 50% less than the sum of the strengths of the individual fibers. It is quite possible, Professor Rubinsky says, this loss is due to lack of plasticity of glass. It is thus important to develop a type of strand or cord that would have a high effective strength.

"Just as essential is the necessity for finding the proper size of cords to be used.

"Glass fibers can be used to apply prestress through bond or through end anchorages without bond. In the latter case, Professor Rubinsky suggests forming the member with longitudinal grooves into which glass cords will be placed. Continuous around the member, the grooves should be so shaped as not to have any sudden change in curvature to avoid overstressing cords at sharp corners. Minimum allowable radius of curvature would be determined by strength of concrete, working stresses in the cords and cord diameter.

"To apply the prestress, one end of the cord would be anchored to the concrete. Then the cord would be wound into a continuous groove under calculated tension. Finally, the second end should be anchored to the concrete.

"A word of caution is necessary, however. As the cord is wound around the groove, the member deforms, the amount of compressive strain increasing as successive layers of cord are applied. This tends to decrease the stress in the layers placed first. Fortunately, as Professor Rubinsky points out, the modulus of elasticity of glass cord is small, so that the loss of stress is almost negligible and can be easily taken into account in design calculations if desired.

"For countries that import steel or do not have sufficient quantities of it, replacement of steel by glass offers tremendous economies, Professor Rubinsky concludes. Especially since natural supplies of silica for making glass are available practically everywhere."

11. In August 1951 Rubinsky prepared a report of his work at Princeton. This report has not been published, but a copy was loaned for examination by the USNCERE Laboratory. The report includes a review of

the literature, a description of the experiments conducted by Rubinsky mostly during the spring and summer of 1951, and conclusions and suggestions for future experiments.

12. The tests covered by the report consisted of tensile and flexural strength determinations on various glass-fiber specimens, creep tests, a limited investigation of static fatigue, the effect of water and alkalies on fiber glass, tests of the bond between the fiber glass and the concrete, and finally the making and testing of two beams. One of the beams was prestressed with fiber-glass rods and the other poststressed with fiber-glass cords.

13. Rubinsky lists the following conclusions based on his experimental work:

a. "Fiber glass bonded with polyester resins is a practical material for prestressing concrete, both by post-tensioning and by pretensioning by direct bond.

b. "All the experiments have shown an absence of creep, both in cordage and in the fiber-glass polyester rods. The material is perfectly elastic and brittle. These properties create certain difficulties in anchorage problems.

c. "One of the most important phenomena encountered in connection with the material tested was that of static fatigue. Static fatigue varies with the percentage of the ultimate tensile or flexural stresses to which the sample is subjected. Apparently the values of the ultimate stresses have to be always determined for certain rates of loading.

d. "The 'Bow Method' flexural test was developed during the experiments to eliminate to a great degree all except the flexural stresses. Thus it can be used successfully both for finding the ultimate strength and for determining the static fatigue characteristics of the material.

e. "Cordage bonded by Geon plastics loses its strength considerably under the action of alkalies found in cement and even under the action of plain water.

f. "The type manufactured by Sportsmen Accessories, Inc., appears to be a strong material as the glass fibers in it developed a strength of 200,000 psi; however, the effects of alkalies and water have not yet been investigated.

g. "In concrete prestressed with fiber-glass rods, bond depends on the roughness of the surface, the diameter of the rod, and the amount of prestress applied to the rod.

h. "In prestressing by post-tensioning with cordage, precautions must be taken to reinforce the sides of the grooves of the beams. If tapes instead of cordage are used, quite possibly such reinforcing would not be necessary if proper consideration is given to the type of binding plastics. Side pressures must not be allowed to develop."

14. The first account published by Rubinsky was in the Magazine of Concrete Research[64]. It includes references to the work initiated by him at Princeton in 1951 and states that this work was continued by Mr. K. W. Mean. Acknowledgments were made to Princeton University and to Dr. Ray E. Cregps for permission to use certain photographs. This account includes the following:

"The high cost and shortage or absence of some building materials, together with the almost universal shortage of housing, have led many to initiate research in cheaper and commoner substitutes to traditional building materials. Steel, which is everywhere in short supply and in many countries is not produced at all, is one of the most costly and most important building materials.

"This shortage of steel during and after the Second World War was the major impulse to the development of prestressed concrete. This development would be still more valuable, however, if it were possible to substitute for the steel a material which could be produced everywhere. Glass, in the form of fibre-glass, may provide the solution.

"The purpose of this article is to provoke interest in the possibility of using fibre-glass, and to inspire further research into the problems entailed, as well as suggesting lines for future experimental work.

"Attempts have been made to substitute fibre-glass for steel in reinforced concrete (Jackson patent), but all such efforts are doomed to failure because of the low modulus of elasticity of glass compared with that of steel; as the elastic modulus of glass is only about twice that of concrete, very little of the tensile stress will be transmitted from the concrete to the glass reinforcement, while the difference in strength between the fibre-glass and the concrete is very large.

"In prestressed concrete, however, conditions are very different.

The low elasticity of fibre-glass is a great advantage, since losses of prestress due to creep, shrinkage, elastic strain and temperature changes in the concrete, usually taken as 15 to 20 per cent when high-tensile steel is used, would be reduced to a very low figure.

"Physical properties of fibre-glass

"The high strength of glass fibres is well known. According to the work of Anderegg, Reinkober, Jurkov, Aslanova and many others, values as high as 3×10^{6} to 4×10^{6} lb/sq. in. have been attained. The highest experimental value of 5.2×10^{6} lb/sq. in. for fused silicon* fibres of 3.1 microns diameter is given by Aslanova[4].

"The products which are commercially available do not, of course, reach these values of tensile strength, but considerable progress is being made. For example, a type of fibre-glass manufactured by the Owens-Corning Fiberglas Corporation for the reinforcement of plastics possesses an average strength of 270,000 lb/sq. in. according to their official statement[54]. The Research and Development Laboratories of the Corporation give the following information:

"The highest stresses obtained with glass fibers are 500,000 to 760,000 lb/sq. in. These are strictly laboratory values secured on freshly formed and carefully protected fibers. Ultimate tensile strengths of continuous filament strands commercially available range from 150,000 to 400,000 lb/sq. in. depending on the coating, surface treatment and handling. The modulus of elasticity of fibre-glass fibers is about 10×10^{6} lb/sq. in. Perhaps one of the best recent accounts of the physical properties of glass, with particular reference to its mechanical strength, is that given by Stanworth[71], which includes an extensive bibliography. In addition to describing the various physical properties of glass, the author reviews the theories of strength put forward by Griffith, Orowan, Murgatroyd, Gurney, Taylor, etc.

"All authors agree that the phenomenon of high strength is dependent upon the diameter and length of the fibre: the strength increases considerably with decreasing diameter and length.

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*. Sic. Must mean silica. Ed.

[illegible] cooling of the surface [illegible] with that of the rest of the fibre, and no surface [illegible]. Furthermore, it has been shown that [illegible] the surface with hydrofluoric acid not only did not decrease the ultimate strength, but actually increased it, in some cases up to 100 per cent ([illegible], Turner).

The most plausible theory is that of Griffith. The wide variation in strength of glass is supposed to be due to the existence of defects or minute cracks in the glass, causing an uneven stress distribution under loading, and leading to early failure. Naturally the smaller the diameter and the shorter the length, the lower the proportion of irregularities and hence the higher the strength. It is also possible that, during the manufacture of the fibres, the drawing tends to elongate the defects parallel to the axis; the finer the fibre the greater will be the elongation, which would tend to reduce the local stresses and so increase the ultimate strength of the fibre.

Another important property of glass fibres is that their strength varies with the moisture on the surface. Drying a fibre in an oven will double its strength, and drying in a vacuum may increase the strength to 3-1/2 or 4 times its original value.

Turner believes that this phenomenon is due to the surface cracks and flaws being filled with gels of silicon* which, when exposed to humidity, swell and set up local internal stresses, thus weakening the material.

Many investigators have established that the duration of loading has a pronounced effect on the strength of glass plate and rods, known as 'static fatigue' (Holland and Turner, Preston, Baker and Preston). The author has not found any similar experimental data in regard to glass fibres, however, as static fatigue is closely related to loss of strength

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* Sic. Must mean silica. Ed.

due to surface moisture, it is very likely that static fatigue also exists in fibres, but this remains to be verified experimentally.

"As glass fibres are very brittle, it is necessary to protect the glass yarns and cords by some kind of protective layer. This is necessary not only to prevent breakage of individual fibres due to abrasion, but also to bind them together and produce a more even distribution of stresses.

"Various forms of fibre-glass are commercially available. These include fibre-glass yarns and cords made up of twisted strands with several surface treatments and glass fibre rods and tapes, some of them made up of unidirectional fibres, bonded together with plastics or resins. Polyester-bonded fibre-glass rods are among the most convenient forms of fibre-glass for prestressing so far found by the author. The saturated polyesters do not require high pressure during moulding and laminating operations, and the curing temperatures are usually in the range from 225 to 275 F. During the curing cycle these resins themselves generate heat, facilitating the moulding operation.

"The tests carried out by Professor Rubinsky were on polyester-bonded fibre-glass rods of 1/4 in. diameter, specially manufactured for him by the Columbia Products Co. (U.S.A.). The ultimate strength of the rods was found to be 147,000 lb/sq. in. and the modulus of elasticity about 7×10^6 lb/sq. in.

"The experiments showed that the load which could be sustained was dependent upon time. As however, an unreinforced sample of the bonding plastic was not available for test, it was not determined whether this effect was due to static fatigue of the glass fibres or to creep of the bonding material.

"A simple method was developed to determine the flexural strength under the action of a sustained moment. The ends of a fibre-glass rod were clamped into small grips; the grip at one end was fixed, and the other grip forced towards it by means of a cord with a weight attached, thus forcing the rod into a bow shape. The distance between the two ends was measured for each loading.

"The above provided an easy means of loading the rods to a

given percentage of the breaking moment, by bringing the two ends together with a turnbuckle and measuring the clear opening. As the conditions are those of nearly pure flexure, it was quite simple to calculate the stresses developed.

"The reduction in strength due to absorbed moisture and static fatigue is of prime importance and, before fibre-glass can be used successfully for reinforcement, further research must be carried out to determine the factors affecting it and, perhaps, ways of eliminating it altogether.

"According to Baker and Preston[7] very little evidence of fatigue remains after drying in a high vacuum; the obvious answer thus seems to be to protect the glass surface from coming into contact with moisture. One method of achieving this is to apply a special size (e.g. vinyltrichlorosilane) to the glass fibres of plastic-bonded fibre-glass during the manufacturing process (Stanworth, Yaeger). After drying, the fibres are washed with water, which is believed to hydrolyze off the chlorine so that the silicon atom can bond to the glass while the vinyl group participates in the resin polymerization, producing a strong bond between the glass and the resin and protecting the glass fibres from moisture.

"The transmission of the tension from the reinforcement to the concrete has always been one of the major problems in prestressed structures. With fibre-glass reinforcement this problem is even more acute due to the brittleness of the material. The transmission may be effected in any of the following ways:

(a) by direct bond with the concrete;

(b) by compression and shear in jaw grips;

(c) by bearing (e.g. winding cords round pipes or round webs of concrete beams);

(d) by bond between fibre-glass and grip by the use of an adhesive.

"Preliminary experiments done by Professor Rubinsky show that sufficient bond can be achieved by method (a). The bond depends predominantly on the surface of the rods or cords, and various types of treatment,

such as corrugations on the surface, are desirable. A maximum bond stress of 1,050 lb/sq. in. was reached with a rod of 1/4 in. diameter embedded in concrete.

"The design of suitable grips - either temporary, for pretensioned concrete, or permanent, for post-tensioned concrete - presents a major difficulty, as the brittle rod is liable to fail in the grip itself due to the combined effects of shearing and crushing stresses added to the tensile stress. An ideal grip must be such that the tension is transmitted gradually from rod to grip. A few designs of grips have been tried, such as two grooved plates bolted together, the bolts being of varying size so calculated that the centre of gravity of their cross sections was one-third of the distance from the testing-machine end of the clamp, but further experiments are necessary to find a really successful grip. Good results have been achieved by Keane, who used a grip consisting of a 1/4 in. pipe, 12 in. long, with the fibre-glass rod bonded to it by a cold-setting resin. The adhesive must be selected with care, however, to minimize creep.

"Tests on model beams

"Tests on two types of model concrete beams were made by Professor Rubinsky. One type, 3 x 4-1/2 x 36 in. long, was prestressed by two 1/4 in. diameter polyester-bonded fibre-glass rods. The other type was of similar size, but with a circumferential groove 1 in. wide and 1/2 in. deep; after curing, this beam was post-tensioned by means of a Geon-coated fibre-glass cord of 0.042 in. diameter wound round the beam at a constant tension.

"Both types of beams were loaded to destruction. The first type proved successful and withstood loads slightly higher than predicted. In the second type the edge of the groove sheared off, due to the lateral pressure of the cords. Unfortunately time did not permit a repetition of the experiment with the edges reinforced.

"The research carried out by Professor Rubinsky was of a preliminary nature, primarily to determine whether or not it is feasible to use fibre-glass as reinforcement for prestressed concrete and to gather data on the physical properties of fibre-glass.

[illegible]

"The tapes can be [illegible] the required tension. Alternatively, the beam can be made in two halves and the tapes [illegible] loosely. The two halves can then be jacked apart, thus tightening the tapes, and the space between the two parts of the beam filled with quick-setting concrete. This procedure has been used in post-tensioning ordinary beams with steel wires and has proved quite practical.

"This method of prestressing has the advantage that no expensive apparatus is required. The tapes can be attached without special grips designed to sustain the whole tension, which would require much additional research.

"It is of course desirable to use tapes manufactured from continuous fibres treated with vinyltrichlorosilane, in order to double the average tensile strength and eliminate possible static fatigue.

"Although it is more spectacular to experiment directly with model beams, the authors believe there is much groundwork to be done first. A superior quality of fibre-glass, chemically protected against the effect of humidity, must be developed industrially, and further experiments carried out on the product, with particular reference to static fatigue.

"Reliable values of the tensile strength and the modulus of elasticity of fibre-glass products should be determined, based on a large number of tests. Methods of increasing bond, and improved types of anchorages should be developed.

"Suitable plastic-bonded fibre-glass reinforcement would be particularly valuable for prestressing structures exposed to corroding forces such as sea water.

"When all these problems have been solved, glass reinforcement for concrete will compete seriously with steel, bearing in mind that with possible improvement in the manufacturing process a product with an ultimate strength of 1,000,000 lb/sq. in. may be achieved. Compared with

cold drawn steel wire with an ultimate strength of 224,000 lb/sq. in., as is at present used for prestressed concrete; the amount of glass fibre required would be about one-quarter by volume, and about one-thirteenth by weight of that of high-tensile steel. If ordinary reinforced concrete were replaced by concrete prestressed by fibre-glass, the amount of glass required would be about 1-1/2 - 2 per cent of the quantity of mild steel.

"It is thus evident that the use of glass instead of steel would lead to considerable saving. For countries that import steel or do not have sufficient quantities of it, replacement of steel by glass would result in a tremendous national economy, especially since natural supplies of silica are found practically everywhere in the world."

Work of Crepps

15. Crepps[23] presented a summary of information including the following, but made no reference to Rubinsky:

"The feasibility of taking advantage of certain physical properties of glass fibers for application and use in the tensioning element of prestressed and poststressed concrete structural members is indeed intriguing to both engineering designers and constructors. Much interest in this subject, largely academic, has been shown during the past ten months, although constructors and fabricators are anxious to cooperate in any workable enterprise to verify design considerations for practical usage. Before any practical application of glass fibers in prestress structures is justifiable, considerable experimental investigations are necessary.

"This paper is not intended to be a report on specific research in this field of engineering but is given to convey the important properties of glass fibers useful in prestressing, and to point out several problems of concern in the application of commercially available glass fibers and products.

"Design considerations of prestressed concrete structural members depend upon the two important physical properties of the tensioning element, namely strength and stiffness. A high unit yield or ultimate tensile strength is desirable from an economic viewpoint but not necessary

on a structural basis. The stiffness, or modulus of elasticity, of steel straight rods and wires is a constant value of about 30,000,000 psi, and for cables it is somewhat less depending upon the cable construction. However, the high loss of 15 to 25 per cent in the steel prestress due to shrinkage and flow of the concrete, points to the desirability for use of a lower modulus material.

"In the Walnut Lane Bridge, Philadelphia, Pennsylvania, the cables employed 0.276-inch diameter high carbon steel wires that had a yield point strength of 213,000 psi, although the design called for only 160,000 psi. A glass rod of this size possesses only a fraction of this strength; however, if the same cross-sectional area of glass is made into fine filaments, their combined strength is greater than that of the steel wire.

"In order to produce fine glass filaments of durable quality, special borosilicate glass compositions are selected. The batch ingredients are melted in a furnace comparable to that used in making open hearth steel and after a period of four or five days the glass, at a temperature of about 2,300 degrees, is formed into marbles about 13/16 inch in diameter. These marbles are melted in small electric furnaces and the glass flows by gravity through 204 small openings in the bottom of what is termed a bushing. These several small streams of glass are drawn into tiny filaments connecting them to a 6-inch-diameter drum which spins at the rate of 6,400 rpm. One marble yields 95 to 250 miles of single filament depending upon the diameter. The production rate of a strand of 204 filaments approximates two miles per minute. The strand is removed from the drum and wound in a form convenient for its intended end usage.

"References in literature point to high tensile strengths of over 1,000,000 psi for laboratory produced fine filaments. The tensile strength of glass filaments is high and, in a general way, is associated with the size increasing as the fibers become finer. However, in the practical present-day commercial textile fibers the ultimate strengths range between 250,000 and 350,000 psi. More recent experience has shown that by proper techniques in the control of the several variables encountered in making glass textile filaments, from 0.00020 to 0.00040 inch

in diameter, strengths of approximately 200,000 to 300,000 psi are obtained regardless of the filament size.

"A stress-strain diagram for glass filaments in tension is essentially a straight line to the rupture point. There is no characteristic yield point or yield strength as expected for steels. The stiffness or modulus of elasticity (E) for single filaments is 8,000,000-9,000,000 psi.

"Glass filaments are very flexible yet are exceptionally elastic. They show no measurable plasticity under high unit stress and as concluded for Fiberglas yarn ECD 900-1/2 in a recent released report* from the Army Quartermaster General's office. 'Therefore practically no permanent set is observable as a result of applied strain.' Glass weighs about one-third as much as steel; the specific gravity of glass is 2.54 while that for steel is 7.8.

"Yarns of Fiberglas are made by combining several strands, of 204 filaments each, which are twisted and plied. The combination of number of strands, their twists and plies are governed by their intended use. By comparison, their tensile strengths, when determined by the ASTM D 578 Methods of Tests for glass yarns, are, on an average, about 60 per cent of that for an equal number of straight filaments. The modulus of elasticity for yarns is also lower than for single filaments, the exact value depending upon the construction of twists and plies, but will range from 4,000,000 to 8,000,000 psi.

"Several manufacturers of reinforced plastic rods incorporate a number of strands of glass filaments in parallel as the reinforcement in the plastic. These rods have tensile strengths per unit cross section only slightly lower than, but somewhat in proportion to, the combined strength of the number of individual filaments used. Strengths of 210,000 psi have been obtained per unit cross section of the rods; however, strengths of currently produced rods approximate 130,000 psi. A

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* Research and Development Report, Textile Series. Report No. 64, "Tensile Recovery Behavior of Textile Fibers," by George Susich and Stanley Backer, Department of the Army, Office of the Quartermaster General.

limited number of tests show practically a straight line stress-strain curve to the rupture point for reinforced plastics with parallel fibers. The modulus of elasticity ranges from 4,000,000 to 7,000,000 psi. The specific gravity of the rod stock is about 2.0.

Another inherent property in glass fiber reinforced plastic is the great impact resistance. The Izod impact resistance of bars is about 70 foot pounds, which is many times that of heat-treated high-carbon steels.

"A number of investigative problems present themselves when one considers the fabrication and subsequent behavior of structural members prestressed with glass fibers. It is readily conceivable that individual filaments, of such small size that they can be seen only with difficulty, could not be handled expeditiously. Therefore, some of the inherent strength of single filaments must be sacrificed in using combinations of them either in the form of yarns, cords, or cables, or in plastic rods wherein the filaments would be bonded in a parallel manner.

"How can the glass tensioning member be stretched so that each filament has the same stress throughout a combination of yarns or throughout the cross section of plastic rods? This problem is not simple and would require considerable work to know how to fulfill these conditions. It has been found in the tension testing of glass yarns and cords, as well as plastic rods, that considerable effort is expended in obtaining sufficient holding power to cause failure outside of the grips. Slippage is caused by the smoothness and hardness of the glass surface; and, too, the hardened points of serrated surfaced metal grips tend to break the surface fibers in plastic rods. These phenomena suggest special attention need be taken in the development of a suitable mechanical anchorage, such as may be employed in poststressing. Any mechanical or hydraulic device used in straining should be capable of three to five times the movement encountered with steel because of the differences in the moduli of elasticity.

"If plastic rods are used in a bonded prestressed member, how efficient and how durable is this bond? Studies need to be made to determine the magnitude of bond between the several kinds of plastics employed

in place of rods of high area in concrete mixes. The influence during aging under several conditions of moisture from dry to wet should be included. Would any cold flow of the plastic be developed with time, when glass reinforcement rods are subjected to high unit stresses? Research is needed to determine the magnitude of stress, size of rods, percentage of glass filament area in the total cross section of rods, with respect to stress and relaxation and time. A completely reliable technique for testing glass-plastic rods in tension needs development, since difficulties are encountered in holding the rods in the testing machine jaws when employing known standard methods for metals and plastic laminates.

"Can a higher percentage working stress be used for glass fibers than for steel when one recalls that (1) the former has no yield point, and (2) stress release in the tensioning member of glass will be proportionately lower than for steel, since the moduli of elasticity for concrete and glass are more nearly equal than for concrete and steel?

"What will be the relative stress increase in the glass tensioning member and the stress decrease in the concrete on the tension side, when live load is placed on a beam structure, particularly when one recalls that the moduli of elasticity of the two materials are more nearly equal than in the case where steel reinforcement is employed? Mr. T. Germundsson,* Portland Cement Association, in a paper presented in an earlier session of this conference, showed that the increase in prestress developed in the tensioning steel due to superimposed loads on a beam was practically nil. He also pointed out that the tensioning prestress had little influence on the subsequent load-deflection characteristics of the beam up to the transition point when tension cracks would be developed in the concrete. A tensioning material of lower modulus of elasticity should not alter this characteristic. However, special attention should be given to the stress relationship in regions above incipient tension cracking.

"The question of durability of glass fibers embedded in

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* "Prestressed Concrete Design Concepts," T. Germundsson, Structural and Railways Bureau, Portland Cement Association, Chicago, Illinois.

[illegible] may result. Experiments have been [illegible] adhesion [illegible] the surface of crushed glass used as ag- [illegible] experience [illegible] the use of glass fibers. It is [illegible] that a pH of about 12 is essential in the hydration of Portland cement and that an environment with a pH of more than 8 or 9 is undesirable for most glasses.

There are literally hundreds of compositions of glass, some of them are superior to others, in the presence of alkali. The present-day commercial textile fibers are made from borosilicate glasses of such composition that they are practically alkali-free and have better resistance than most glasses to a high alkaline environment. Treatments are known which will protect glass against alkali but their influence on bond strength, which may be important in bonded type prestressed members, needs investigation. It is questionable as to how serious an alkaline condition in concrete would be in the cases of bonded, or unbonded, glass cord or yarn tensioning members in prestressed concrete. It is known that concrete forms a corrosion protection to steel and there might be a comparable protection afforded to glass cables, particularly where little or no migration of vapor moisture would be encountered. In the case where glass plastic rods would be employed as the tensioning member, this problem is greatly minimized since it is known that several plastics are resistant to alkali to at least a pH of 12. Regardless of what form glass filaments would be used in a tensioning member, studies designed for chemical stability of the particular materials used in prestressed members should be included in any complete investigative program.

The development of continuous glass fibers has been dictated by the type and kinds of markets that would use them in such volume as to make possible a decrease in production costs to the extent that they become competitive with other materials. Such volume markets now are found in the field of textiles, electrical insulation, and reinforcement of plastic. Available on the market are continuous glass filaments ranging from 20-60 hundred thousandths of an inch in diameter, in the form of strands, yarns, cords, cables and ropes. These products are generally used for special purposes where certain desirable properties are essential,

such as in cases where high strength, low weight and corrosion resistance are important. Glass-plastic rod stock, in sizes suitable for reinforcing concrete, is also available from a large number of producers.

"At the present time engineering interest is mounting rapidly in prestressed concrete - not because of shortages of materials for this market but because of physical and mechanical advantages for this type structure. The high strength and low stiffness properties of glass fibers, as well as other properties when used in plastic rods, might be taken advantage of in their use as a tensioning member in prestressed concrete. However, since their use at the present time is practically nil, it is recognized that considerable exploratory evaluation must be made in order to discover their useful limitations. How to use the exceptionally high strength of experimental laboratory-produced fine fiber is primarily of future interest and efforts in this direction can be realized only after learning how to use and evaluate the present commercially available materials.

"Active interest in the use of glass as the tensioning element of prestressed concrete has been manifested in the last several months. Among those interested academically are Princeton, Lehigh and Ohio State Universities, Massachusetts Institute of Technology, Portland Cement Association, and others. Several companies now manufacturing precast units have also expressed interest in producing units for field evaluation."

Work of Steele and Libby

16. Steele and Libby[72] described the investigation of the U. S. Naval Civil Engineering Research and Evaluation Laboratories as follows:

"(g) Experimental determination of the suitability of high strength low Young's modulus materials, such as fiber glass as a prestressing cable:

"A rational analysis of prestressed concrete indicates that the material used for prestressing should exhibit a high strain and low amount of creep at the working stress to minimize the losses of prestress due to creep in the prestressing material, as well as shrinkage and plastic

flow of the concrete. This logic, which was used by Freyssinet and others in concluding that the steel used in prestressed concrete must have a high working stress, can be extended to yield relative figures of merit for various materials in determining the value as a prestressing material. For example, the unit strain of high strength steel at the commonly used working stresses of about 120,000 psi is 0.004 in./in. when based on a modulus of elasticity of 30,000,000 psi. This reasoning can be extended to show that a material with an elastic modulus of 10,000,000 psi would have the same strain as a stress of 40,000 psi. The Laboratory concluded that fiber glass has characteristics for accomplishing this purpose, and in order to determine the merits of fiber glass and possibly other materials, the Laboratory has initiated experiments to determine the value of materials other than steel for use in prestressing concrete.

"The program is in the initial phase of establishing the physical properties of various commercially manufactured fiber glass rods and bars. This program was initiated so recently that no results as yet are available. Since the use of fiber glass for this purpose is quite controversial, the projected research plan will emphasize the determination of the following:

1. Economies of using fiber glass in lieu of steel for prestressing.

2. Physical properties of fiber glass.

3. Chemical resistance of fiber glass to the adverse corrosive effects of cement.

4. Prestressing techniques when using fiber glass.

"It is felt that research along the above lines will do much to ascertain whether fiber glass does have a place in the prestressing picture.

"The Laboratory has recently been informed that Professor Ivan Rubinsky, of the American University of Beirut, Beirut, Lebanon, holds a Lebanon patent on the use of fiber glass for prestressing concrete."

Work by Keane

17. Subsequent to Rubinsky's departure from Princeton, work was continued, partially with financial assistance from the Bureau of Yards and Docks, U. S. Navy. Several reports of this work have been prepared but not published.

18. A major portion of the report by Keane[41] deals with experiments with various types of clamps for use in gripping the fiber-glass specimens during various tests. The most promising clamping device tested was a conical grip in which the specimen was held by a plug and cemented in place with resin.

19. Keane's findings with regard to creep are at variance with those reported by Rubinsky[63]. Keane reports as follows:

"In his preliminary reports, Rubinsky described the static fatigue and failure of the rods under various loadings. Using the 'bow method' of flexural testing and a centrally loaded fiber glass rod simply supported as a beam, failure with time occurred with no apparent creep in the rod.

"Under conditions of cantilever loading, creep was detected in the rod. This suggests the following explanation of why fiber glass rods fail at a lesser stress under long time load conditions.

"When a constant load is applied to a fiber-glass rod, some stress is taken by the fiber glass, while some of the stress is taken by the tensile properties of the resin. The properties of the resin are such that it creeps or flows thus releasing a part of the stress carried by the resin. Since the load is constant, the stress released by the resin must be taken by the fiber glass. Thus the fiber glass takes an increasing proportion of the load with time until it reaches a failing stress. Since the rate of plastic flow increases with an increase of load, it can be seen that at heavier loads the rate of transfer of stress from resin to fiber glass will increase, causing failure of the rod in a shorter period of time. This explanation applies to fiber glass rods tested in flexure or in tension. The magnitude of shearing strains resisted by the plastic in flexure tests indicates a short time tensile

strength (in tension equal or exceeding static [illegible]) of sufficient magnitude to influence [illegible] of the glass. Differences in the modulus of elasticity will not [illegible] the qualitative value of this theory.

Static fatigue is believed to exist in other forms of glass and this argument does not deny the possibility of the existence of static fatigue within the glass fibers themselves, but it does suggest that the effect of static fatigue of the glass fibers in fiber glass rods as determined by the [illegible] of tensile tests may be in error and the load versus time effects not as serious as indicated."

20. Tests of the bond between fiber glass and concrete conducted by [illegible][14] show that the bond developed is dependent upon the adhesion properties and roughness of the material covering the rod. It is suggested that large-grained sharp-angled carborundum covering for the fiber-glass rods might provide the best bond.

21. [illegible]'s tests of a prestressed fiber-glass reinforced concrete beam indicated satisfactory short-time performance; it was suspected, however, that the specimen would have been less efficient in long-time performance due to plastic flow in the bond to the concrete.

22. A modified conical gripping device, the "Steel Cube standvise," was announced in 1957 (Reliable Electric Company). It consists of a reusable gripping chuck, available in six sizes, for end anchoring wire, strand, or rod which is said to hold firmly from 300- to 20,000-lb tension.

Work of Sollenberger

23. Angus and Sollenberger[3] report the development of an end connection patterned after a Standard Roebling Strand Socket, which is believed to be reliable for determining tensile strength of 1/4-in.-diameter fiber-glass rod. They found the modulus of rupture and the tensile strength of 1/4-in.-diameter rod containing 54 per cent glass by volume to be 150,000 to 200,000 psi and 100,000 to 120,000 psi, respectively. They regard the working stress as one-half the axial ultimate tensile strength.

28. These authors, in discussing the most practical method for fabricating prestressed concrete beams, state the following: "Fiber glass rods as received from the fabricators have a relatively smooth surface which when cast in concrete does not develop the desired bond. However, when the rod is coated with a plastic and rolled in a sharp sand before the plastic is cured, the result is a 'sandpaper' surface which develops considerable bond."

To date the method of fabrication of prestressed beams found most practical is the pretensioned bonded method. End connections are placed on surface-treated rods, the rods are pretensioned, and the concrete is cast in the forms. After the concrete cures, the beams are prestressed by releasing the anchorage and the rods are cut at the face of the concrete. Thus the sockets for the end and connections of the rods are salvaged."

29. Sollenberger supervised the work of Keane, Weis, and Surko at Princeton and in 1953 prepared a summary of the available data that included some work not reported elsewhere. He summarizes the actual tests that had been made of concrete beams prestressed with fiber glass:

a. In August 1951 Rubinsky fabricated and tested a beam prestressed by winding a precast concrete beam with a fiber-glass cord wound in a groove.

b. In 1952 Crepps used fiber-glass twine to prestress a floor beam composed of precast cinder blocks. Cables were fabricated by placing loops of twine about end shoes so that a uniform tension was obtained in all loops. The end was then secured and the shoes rotated to give a twisted strand. The strand assembly was threaded through 8- by 8- by 16-in. cinder blocks to form a beam 16 ft 18 in. in length. The strands are located at the centroid of the cross section of the beam at the ends and deflected 1-5/8 in. by a bearing saddle at each quarter point. Except at the saddles and ends, the strands are suspended in the air spaces within the blocks. The beam, over an effective span of 16 ft, was subjected to a floor loading of 100 lb per sq ft. After several months the beam was still capable of supporting its design load.

c. Beams 3 by 4-1/2 in. by 6 ft have been made at Princeton, prestressed by two 1/4-in. rods placed one-third the distance from the bottom to the top of the beam. The initial tensioning was 61,000 psi and the estimated loss in stress due to shrinkage of the concrete was only 5,000 psi.

Smaller beams 2-1/2 in. by 3 in. have also been used to study the properties of the rods.

d. In the spring of 1953, concrete lintels prestressed with fiber-glass rods were being fabricated to replace deteriorated reinforced concrete lintels in certain small laboratory buildings built at Princeton during World War II.

Work of Weis

26. In June 1953 Weis reported on further developments at Princeton University relative to the use of fiber glass for prestressing concrete. The work by Weis was aimed primarily at investigating the existence of an endurance limit for fiber-glass rods and the evaluation of this limit should it exist.

27. Weis states as follows: "It was the intention of this particular phase of the investigation of the feasibility of fiber glass for prestressing concrete to investigate the existence of endurance limit in the fiber glass rods being used in the tests. Such a series of experiments necessitated the application and removal of varying intensities of stress a very large number of times. Since the rods under consideration were 1/4-inch diameter rods and had displayed an ultimate tensile strength of upwards of 160,000 psi, such an investigation would require the application of loads in the range of 3000 pounds to 5000 pounds. The repetition of loads of this magnitude made such an investigation of repeated over a large number of specimens almost beyond reason. In addition, since previous complications had been met in perfecting a suitable end anchorage connection which would not cause excessive stresses in the gripping arrangements, a method of testing was sought which would cause the failure of the rods independent of the end connection.

"As a result of these considerations, it was decided that an ideal manner in which to carry out the proposed endurance limit tests would be to construct prestressed beams in such a manner as to reduce the action of flexural stresses in the rods to a minimum and to provide a means of computing the axial tension in the rods under varying degrees of loading.

This test also provided a means of observing the behavior of a prestressed member under the action of repetitive stresses. It should be noted, however, that the primary purpose of these tests was to observe the effects of repeated load loading on the fiber glass rods and not to investigate prestressed concrete subjected to repeated applications of load."

28. The beams used by Weis were composed of mortar that was designed to have a 28-day compressive strength of at least 4000 psi. The beams were 36 in. long, 2 in. wide, and 3-5/8 in. thick. The prestressing rod was placed at a depth equal to two-thirds of the total thickness of the beam. A method was devised for locating the point of application of the compressive forces in the upper portion of the beam and at the same time eliminating any tension-resisting forces in the bottom fibers of the member, thus necessitating the fiber-glass rods to sustain the entire tension forces resisting the bending of the member.

29. A repetitional loading machine was used in the investigations of the fatigue phenomenon in fiber glass. The cycle of loading required a 30-sec application of load each minute. The applied load varied from 300 to 780 lb.

30. Based on the results of these tests, Weis concludes as follows: "The endurance limit for fiber glass rods as determined from these experiments is approximately 52% of the ultimate stress. However, in those tests simulating conditions found in actual practice, this endurance limit percentage may be found to be appreciably greater."

Work of Surko

31. The third Princeton Master's thesis produced in connection with the work on the use of fiber glass for use in prestressed concrete was that by Alexander Surko, Jr.[73]. The portion of the program studied by Surko was the determination of whether or not the strength of the fiber glass in a fiber-glass reinforced plastic rod could be more fully developed. He showed again that glass-fiber strength varied with composition, fiber diameter, and surface condition. Silica glass in small fibers

with a proper sizing to protect the surface [illegible]. Silica glass in fibers less than 0.1 micron in [illegible] ultimate tensile strength well in excess of 100,[illegible] psi. [illegible] glass content, the greater will be the strength of [illegible] rod. Theoretically, nearly [illegible]0 per cent of the [illegible] tually, 75 per cent is the maximum practical glass content. [illegible] other properties are also beneficially affected by [illegible] fiber-glass mesh tape wrapping to support the [illegible].

32. Surko gives test results on 22 rods. [illegible] tensile strengths of the eight "high-strength" [illegible] Stress-strain curves on eight rods indicate [illegible] elasticity with little, if any, ductility. [illegible] elasticity was [illegible] to [illegible] x 10^6 psi. He concludes that [illegible] tensile strength of a rod will be about [illegible] of the glass. If glass fibers of 1 x 10^6 psi [illegible] produced, fiber-glass reinforced plastic rods of [illegible] 1.2 x 10^5 psi could be fabricated from them.

[illegible]

33. [illegible] sium, calcium, or barium. [illegible] the [illegible] process or the [illegible] process. [illegible] fiber [illegible] balls [illegible] the fiber [illegible] continuous-fiber [illegible] fices [illegible] stretching [illegible] thread size. [illegible] fiber is resistant to [illegible] temperatures.

34. [illegible]

by an anomalous increase of viscosity with increasing tension. This is a consequence of the molecular constitution of the melt and is possible only if there is an orientation and distortion of the molecular ingredients during the elongation of the fiber.

35. Murgatroyd[47] studied the mechanical properties of glass fibers and determined the modulus of rigidity and Young's modulus of elasticity as functions of fiber diameter. He also developed a relationship for the rupture strength of glass filaments as a function of time (see Eitel[29], p 300).

36. Rexer[61] studied the effects on tensile strength of glass fibers of initial tensions and other conditions of production and made evident that the steep increase in tensile strength with decreasing diameter is the consequence of a much reduced number of inner flaws in the fiber. The extension structure of the fibers brings about a strongly prestressed condition in the exterior zone, which must additionally be overcome in the tension test. Rupture most frequently starts in the surface layer of the fiber in which the flaws are located; if this "defect" surface layer is removed by etching with hydrofluoric acid, the flaws are also removed and the fiber is strengthened up to 300 per cent. After removal by etching of a layer 0.5μ thick the fibers attain maximum strength. Freshly produced fibers have higher strength than aged fibers (see Eitel[29], pp 298-300).

37. Two classes of glass fibers are defined by ASTM Designation C 162: (a) continuous fibers are filaments of great or indefinite length, and (b) staple fibers are of relatively short length, generally less than 17 in. The same reference noted that borosilicate glass is glass that contains at least 5 per cent boron oxide (B_2O_3).

38. Baker and Preston[7] confirmed the existence of fatigue of glass under static load when rods 7/32 in. in diameter were tested, but found that it disappeared when the glass was tested in vacuo.

39. Blum[11] describes the use of internal damping studies of fine glass fibers, in vacuo, at low frequencies and constant temperature to evaluate the effects of fiber diameter, HF etching, and similar factors to develop information on deviations from perfect elastic behavior.

Reactions between Cement and Glass

40. Brown[13] describes and figures a portion of a portland cement mortar bar in which the aggregate was pyrex glass. The bar showed 0.6 per cent expansion in 3 months. He also describes and figures a portion of a vertical section through a glass insert in an old skylight panel in Chicago. The panel unit was bowed like a pillow, evidencing considerable expansion, and the glass inserts were badly cracked. The glass showed extensive spalling parallel to the boundary between it and the mortar and also internal transverse fractures that start mostly in the spalled border zone. The Department of Scientific and Industrial Research of Australia reported* an example of severe chemical reaction between portland cement mortar and glass tile wall surfacing in a bathroom. Observations of the chemical reactivity of glass and the alkalies in portland cement were responsible for the concern expressed by H. S. Meissner when the notion of glass as a prestressing and reinforcing medium was given publicity in the United States. In 1951 Mr. Meissner wrote:

"Prof. I. A. Rubinsky has suggested that glass fibers would serve as the reinforcing and prestressing medium for prestressed concrete.

"Professor Rubinsky is reported to propose glass reinforcement because it is resistant to acids and alkalies. Many are inclined to accept such a statement readily, since glassware is the common implement of the chemist, who does not hesitate to use it as a container for the most corrosive materials. Yet glass is soluble in alkaline solutions.

"I am told that gin, for instance, is sold in frosted bottles so that the consumer's curiosity would not be aroused by etched glass were it to be packaged in clear glass containers. The pH of gin is so high that the glass is slowly attacked by it. Naturally the consumer would be skeptical about what such a product might do to his stomach if he were aware of what it did to glass.

"Now over 60% of portland cement is alkali material, and it contains small amounts of the very active alkalies, sodium, and potassium.

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* Informal communication.

Much has been written in late years on just how active the latter two are in concrete containing certain siliceous aggregates. These reactive siliceous aggregates are attacked by the cement alkalies, causing expansion and disintegration of the concrete. To measure the extent to which cements are likely to participate in such actions, they have been deliberately put in contact with a highly reactive aggregate prepared by crushing pyrex glass to the granular size of sand. Mortar made with this crushed glass often will expand as much as 0.25% in 2 weeks, and exude calcic- and sodic-silica gels from its surface. I understand that ordinary bottle glass will perform similarly. Therefore, I can imagine that glass fibers with considerable surface area exposed, might turn out to be extremely vulnerable to portland cement paste."

41. Prof. Rubinsky[52] replied to Mr. Meissner as follows:

"H. S. Meissner questioned the practicability of my suggestion for the use of glass fiber for prestressing concrete. His criticism is based upon the fact that glass fibers might be attacked by free alkalies in concrete.

"The possibility of some such action as Mr. Meissner anticipates is well recognized. Any research into the practicability of using glass fibers for reinforcing concrete should investigate thoroughly the chemical, as well as the mechanical stability, of the materials used. The most promising glass-fiber reinforcing material thus far considered consists of parallel fibers embedded in a plastic. Here again, however, the question of the chemical stability of the plastic over prolonged exposure to concrete must be considered.

"At present, I am at Princeton directing the early phases of a program of research into the practicability of using glass-fiber tension members for prestressed concrete. Let me assure Mr. Meissner and other interested engineers that the chemical, as well as the mechanical, phases of the problem will be given consideration."

42. Some fundamental work on the reactions between glass and water has been reported by Beattie[9]. He leached annealed glasses that were crushed and sized to pass 1.003 mm and be retained on 0.599 mm (passing No. 18 sieve, retained on No. 30 sieve, approximately) with highly

purified water at temperatures from 40 to 100 C, removed the reaction products, and determined that the results were best fitted to the assumption that sodium ions diffused out of the glass and hydrogen ions diffused into the glass, the reaction was faster at higher temperature and took less energy to start it with increasing sodium in the glass.

43. Rubinsky's report[13] includes a description of his experiment No. 33, 6 August 1951, on the effects of water and alkalies on a Ceon-coated fiber-glass cord (Type EC 9-3), 0.042 in diameter. Six samples were tested. Two controls give tensile strengths of 97 and 120 lb; two kept in water 25 hr gave 30 lb; and two kept 24 hr in a solution of 200 g of "Incor" high-early strength portland cement and 300 g of water gave strengths of 30 and 35 lb. From the date of this experiment it seems likely that it was stimulated by Meissner's letter. It is interesting to note that the strength reduction was as great after storage in "plain water" as in the cement-water slurry. As a result of these findings, Keane[41] confined his work to rods, noting that "rods are better protected against moisture and cement infiltration than the tapes." The 1953 Princeton report by Angas and Sollenberger[3] states that an important reason for the use of rod rather than rope or cordage is the fact that the fibers in the rod are "so well protected." The amazing resistance to exposure of the fiber-glass fishing rod, as well as the small boat shells made of impregnated glass fibers, is excellent evidence of the effectiveness of this protection. Every piece of evidence so far available indicated that the glass fibers are more than adequately protected from any alkalies present in portland cement concrete.

PART IV: PLASTIC-GLASS SYSTEMS

44. Dietz[26] suggests that there is an analogy between fiber-glass reinforced plastics and reinforced concrete; but in reinforced plastics the fibers are generally much more evenly distributed throughout the mass and the ratio of fibers to plastic is much higher than the ratio of steel to concrete. In designing fiber-glass reinforced plastics it is assumed that the two materials act together -- that in service the strains in the fiber and plastic are equal. This implies that there is good bond between fiber and plastic. It is also assumed that the fiber-glass reinforced plastic is elastic and obeys Hooke's law. This assumption is regarded by Dietz as valid for tension but less for shear.

45. Sonneborn[69] notes that the tensile strength of glass fiber is about 400,000 psi, thus making it the strongest available structural material on an equal weight basis. He compares properties of seven classes of plastics that have been used with fiber glass: polyester, epoxy, phenolic, melamine, silicone, polystyrene, and polyvinyl chloride. Linear coefficients of thermal expansion per deg F parallel to the reinforcement as a function of percentage of glass are reported as follows for polyester resin reinforced plastic:

Glass, % by Weight	Coefficient x 10^6
0	50-60
25	14-18
40	10-15
65	5-6

The yield and ultimate strengths are so close that they are usually considered identical. Sonneborn's book[69] provides a comprehensive survey of information on fiber-glass reinforced plastics and their industrial applications.

46. Batelle Memorial Institute has made a series of studies of plastics and plastic-glass laminates for the U. S. Air Force under contracts administered by the Materials Laboratory, Directorate of Research, Wright Air Development Center. These studies have included glass fabric laminates made with Plaskon 910, Stypol 16B, Selectron 5003, Silicon resin

DC 2104, phenolic resin CTL-91LD, and polyester resin PDL-7-669. A report on the last three by Vanecho, Romely, and Simmons[74] was issued in 1953. Stresses to produce rupture ranged from 19,000 to 36,000 psi in tension and 12,000 to 41,000 psi in compression at 80 F. The ultimate flexural strengths ranged from 29,000 to 63,000 psi, compressive strength 11,000 to 28,000 psi, and flexural modulus of elasticity 2.3 to 3.0×10^6 psi.

PART V: EVALUATION

47. Consideration of the use of materials other than steel for concrete reinforcing is justified under the following conditions:

- a. The alternative materials have engineering properties that are superior to those of steel.
- b. The alternative materials are more economical than steel.
- c. The alternative materials may be expected to be more readily available than steel.

48. It has been noted that the consideration of glass rod and strip in Great Britain in 1940 was based largely on the greater availability of glass at a time when steel was in short supply and great demand. The application studied at that time does not now appear sufficiently promising to merit further study.

49. The consideration of plastic-glass fiber materials as alternatives to steel in prestressed concrete appears to be justified both from the standpoint of advantageous properties and economy. Plastic-glass fiber rods can be made available at approximately four times the cost per pound of steel; however, since they weigh between a third and a fourth as much per unit volume as steel, and may be assumed to have approximately twice the ultimate strength they may be regarded at least as potentially more economical. The advantageous engineering properties derive from the higher ultimate tensile strength and lower modulus of elasticity. Newmark and Siess[59] point out that the advantages from these two factors are not necessarily additive. The low specific gravity would be an important advantage, especially in many military applications.

50. The Rubinskys[64] suggest that to replace cold drawn steel wire having an ultimate strength of 224,000 psi with glass fiber, only about one-quarter of the volume and one-thirteenth of the weight would be required for prestressed concrete, and to replace ordinary reinforced concrete by plastic-glass fiber prestressed concrete the quantity of glass required would be only 1-1/2 to 2 per cent the quantity of mild steel.

51. Steiner[70] expresses the view that "within the next few years materials other than steel will be used for the prestressing of concrete."

He cites the research work at Princeton University, partially financed by the U. S. Navy, on the use of "rods of glass fibres" as prestressing members. He speaks of the technical results so far as "very encouraging" and states that "a small number of concrete beams prestressed with glass fibre rods are already in structural use. As soon as economic difficulties can be overcome, both rods and ropes of glass fibres...can be expected to enter into the prestressing field."

52. Olszak[52] notes that the basic idea of prestressing -- the creation of initial internal forces which act <u>permanently</u>, are <u>strictly determined in advance</u>, and have <u>precisely defined</u> consequences -- permits taking full advantage of "brittle" materials such as concrete, stone, and ceramics which are available in practically unlimited quantities and are cheap, contrary to the "ductile" materials such as steel which are scarce and expensive. He refers to the prestressing of glass by thermal processes and notes that thin-drawn glass fibers are being studied as an active means of prestressing since they have a much higher ultimate strength than steel and are at the same time much lighter.

PART VI: CONCLUDING STATEMENT

53. The review of available information on glass for use in reinforced and prestressed concrete presented in the foregoing paragraphs suggests the following conclusions.

a. The only present field of considerable engineering promise appears to be that concerned with the use of fiber-glass reinforced plastic rods as prestressing elements.

b. The use of fiber-glass reinforced plastic rods in prestressed concrete requires additional study in several different aspects. Some of these relate entirely to the nature, stability, and interaction of the ingredients of the glass-fiber reinforced plastic and do not involve concrete as such. Others relate to use in and interaction with concrete.

c. The following appear to be critical to the successful engineering application of glass-fiber reinforced plastic rods:

(1) The glass fibers should be of some desirable range of fiber diameter, fiber length, and composition in order to provide the desired physical properties and stability.

(2) The plastic should be of a type that provides the desired properties and stability.

(3) The relative amount of glass used in the plastic, its positioning in the plastic, and the mode of fabrication of the fiber glass-plastic system should be such as to develop the desired properties in the system.

(4) The glass-plastic system should be fabricated into structural units of appropriate shape.

(5) The structural units should have appropriate combined properties both as such and as they interact with the concrete.

(6) Appropriate accessories and techniques should be provided for use with the structural units.

d. It is suggested that organizations such as Owens-Corning do the work necessary to establish the information contemplated in items c (1) through c (3) above. Such information would constitute background data to engineering studies designed to provide the information contemplated in c (4) through c (6). With the background data at hand and the engineering studies completed, it would then be practicable to specify the use of glass-fiber reinforced

plastic units as an alternate to steel in a prestressed-concrete construction job. It is not believed prudent to suggest doing so, however, until the results are available.

c. Valuable work has been and is being done, especially at Princeton, to develop the necessary data. It appears, however, that considerable more knowledge should be acquired before the application of glass-fiber reinforced plastic rods as prestressing elements in important construction is proposed.

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